

Panel Report To Fusion Energy Sciences Advisory Committee (FESAC)

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“Review of the International Thermonuclear Experimental Reactor (ITER) Detailed Design Report”

April 18, 1997

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This report was prepared by a Panel established by, and reporting to, the Fusion Energy Science Advisory Committee (FESAC). The report of this Panel has been endorsed by FESAC.

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Glossary of Acronyms

ALARA	As Low As Reasonably Achievable
ASDEX	Tokamak experiment in Germany
ASME	American Society of Mechanical Engineering
AT	Advanced Tokamak
BAE	Beta-driven Alfven Mode instability
BPP	The initial “Basic Performance Phase” of ITER
CDA	Conceptual Design Activities of the ITER program
CFC	Carbon Fiber Composite material
C-Mod	High field Tokamak at MIT
CS	Central Solenoid
CT	Compact Torus
DDD	Detailed Design Description
DDR	Detailed Design Report
DT	Deuterium - Tritium
DIID-D	Tokamak experiment at General Atomics
EC	Electron Cyclotron
ECCD	Electron Cyclotron Current Drive
ECH	Electron Cyclotron Heating
EDA	Engineering Design Activities of the ITER program
EM	Electro-Mechanical
ELM	Edge Localized Mode plasma disturbance
EPP	The second “Enhanced Performance Phase” of ITER
ES&H	Environmental Safety and Health
FDR	Final Design Report
FESAC	Fusion Energy Science Advisory Committee
FMEA	Failure Modes and Effects Analysis
FW	Fast Wave
FWCD	Fast Wave Current Drive
GDR	General Design Requirements
GDRD	General Design Requirements Document
HTO	Hydrogen - Tritium - Oxygen
HTS	Heat Transfer System
H-mode	High (good) energy confinement mode
IBW	Ion Bernstein Waves
IDR	Interim Design Document
ICH	Ion Cyclotron Heating
ICRF	Ion Cyclotron Radio Frequency
ITER	International Thermonuclear Experimental Reactor
ITG	Ion Temperature Gradient
JAERI	Japanese Atomic Energy Research Institute
JCT	Joint Central Team of the ITER design group
JET	Joint European Torus experiment at Culham England
JT-60U	Tokamak Experiment in Japan
KBM	Kinetic Ballooning Mode instability
L-mode	Lower energy confinement mode
LH	Lower Hybrid
LHCD	Lower Hybrid Current Drive
NB	Neutral Beam injection
MHD	Magneto-Hydro-Dynamic
NAG	Nuclear Analysis Group
NSSR-1	Non-site Specific Safety Report

Q	Plasma energy gain (fusion power / injection power)
PCAST	President's Committee of Advisors on Science and Technology
PDD	Partially Detached Divertor
PDX	Poloidal Divertor Experiment
PF	Poloidal Field
PFC	Plasma Facing Components
PGES	Plant Gaseous Effluent Stack
PRETOR	Transport code used by the JCT
RA	Run Away electrons
RAM	Reliability-Availability-Maintainability
RH/M	Remote Handling / Maintenance
RS	Reverse shear
SF ₆	Sulfur hexafluoride
SL-2	Classification for most severe earthquake.
SOL	Scrape-Off-Layer in plasma edge
SWG-1	Special Working Group 1
TAC	Technical Advisory Committee for ITER
TAE	Toroidially Induced Alven Eigenmode instability
TF	Toroidal Field
TFTR	Tokamak Fusion Test Reactor
TPF	Toroidal Peaking Factor
TS	Thermal Shield
USEPA	United States Environmental Protection Agency
VDE	Vertical Displacement Event (vertical movement of the plasma)
WAN	Wide Area Network
WBS	Work Breakdown Structure
β	Plasma pressure / magnetic pressure
ρ^*	ion gyro radius / characteristic plasma size

Preface

Dr. Martha Krebs, Director, Office of Energy Research at the U.S. Department of Energy (DOE), wrote to the Fusion Energy Sciences Advisory Committee (FESAC), in letters dated September 23 and November 6, 1996, requesting that FESAC review the International Thermonuclear Experimental Reactor (ITER) Detailed Design Report (DDR) and “provide its view of the adequacy of the DDR as part of the basis for the United States decision to enter negotiations” with the other interested Parties regarding “the terms and conditions for an agreement for the construction, operations, exploitation and decommissioning of ITER.” The letter from Dr. Krebs, referred to as the Charge Letter, provided context for the review and a set of questions of specific interest.

Addressing the Charge from Dr. Krebs and the specific questions associated with it has been a substantial undertaking because the development of the ITER design involves a wide range of physics, technology, engineering, and management areas. Furthermore, Dr. Krebs’ request for a report from FESAC by May 1, 1997, made the time period for the review limited. As a result, FESAC formed a panel (hereafter referred to as the “Panel”) and charged it to carry out the review, with the objective of presenting a report to the full FESAC before May 1st. This report has been prepared by the Panel and includes our findings, conclusions and recommendations regarding the issues addressed to FESAC.

Eleven subpanels were constituted in January, 1997, three of which were subsequently combined into one. Each of these now nine subpanels was given the responsibility for reviewing particular elements of the ITER DDR report, and providing the Panel with findings and recommendations. The reports of each subpanel are included in this report as a series of appendices. The formation of the subpanels also provided the Panel with the means to hear from and include many outside experts and to insure the broad representation of the fusion scientific and technical community in the review. The Chair of FESAC determined that FESAC members who were employed primarily in ITER activities should not participate in the preparation of the subpanel reports, but should participate to provide clarifying information. The Chair of the Panel agreed to provide copies of each subpanel report to the U.S. ITER Home Team for the sole purpose of checking these reports for factual accuracy. The Panel report itself however has been prepared by the Panel and has received no other review. The membership of the Panel, as well as of the nine subpanels, together with the dates of their various meetings, are given in Appendix A.

Finally, the Panel wishes to express our enormous gratitude to all those who worked tirelessly over an intense six week period to produce the subpanel reports, which in turn informed this Panel’s deliberations, along with the ITER DDR report itself. The Panel is also very grateful to all the members of the ITER international design team, headed by Dr. Robert Amyar, and the U.S. ITER Home Team, headed by Dr. Charles Baker, for their presentations and for their extensive efforts to

provide answers quickly to queries from both the subpanels and the Panel itself. It is clear from the scale and depth of the ITER DDR report that this international team has accomplished an enormous task and our appreciation is extended to them.

I. Executive Summary

ITER, the International Thermonuclear Experimental Reactor project, is now in the Engineering Design Phase (EDA) of a worldwide effort to conceive, design and ultimately construct an experimental device to advance the development of fusion power. The major partners in the ITER effort are the European Union, Japan, the Russian Federation and the United States, and the EDA phase of the program is scheduled to be completed in 1998.

The objectives of ITER are "...to demonstrate controlled ignition and extended burn ...," "...to demonstrate steady-state operation..." and "...to demonstrate the technologies essential for a fusion reactor..." ITER brings together three threads important for the advancement of fusion: burning plasma physics, steady-state operation, and the testing of key technologies. It has long been agreed in the US fusion program that the threshold to burning plasma physics occurs at $Q = 5$, where the alpha heating power equals the externally supplied input power. Technology testing of divertor systems and plasma facing components, as well as qualification of nuclear blanket modules, requires at least 1 GW of fusion power in ITER, with a neutron fluence of about $1 \text{ MW}\cdot\text{yr}/\text{m}^2$ accumulated over a period of about 10 years. Thus if ITER can achieve $Q > 5$ for long pulses at $P_{\text{fus}} > 1 \text{ GW}$, with an availability of 10 - 15%, this will constitute a dramatic step toward demonstrating the scientific and technological feasibility of fusion energy. Together with further improvements in plasma performance and plant availability in the ongoing fusion science and technology programs, results from ITER will provide critical information required for the design of an attractive fusion DEMO power plant.

The general objectives and the plasma performance and engineering performance objectives for ITER are specifically set out in the 1992 report of the Special Working Group-I (SWG-I) as:

General

"The ITER detailed technical objectives and the technical approaches, including appropriate margins, should be compatible with the aim of maintaining the cost of the device within the limits comparable to those indicated in the final report of the ITER CDA as well as keeping its impact in the long-range fusion program. ITER should be designed to operate safely and to demonstrate the safety and environmental potential of fusion power."

Plasma Performance

"ITER should have a confinement capability to reach controlled ignition. The estimates of confinement capability of ITER should be based, as in the CDA procedure, on established favorable modes of operation. ITER should demonstrate controlled ignition and extended burn for a duration sufficient to achieve stationary conditions on all time scales characteristic of plasma processes and plasma wall interactions, and sufficient for achieving stationary conditions for nuclear testing of blanket components. This can be fulfilled by pulses with flat top duration in the range of 1000 s. For

testing particular blanket designs, pulses of approximately 2000 s are desirable, with the ultimate aim of demonstrating steady state operation using non-inductive current drive in reactor relevant plasmas."

Engineering Performance and Testing

"ITER should demonstrate the availability of technologies essential for a fusion reactor (such as superconducting magnets and remote maintenance); test components for a reactor (such as exhaust power and particles from the plasma); test design concepts of tritium breeding blankets relevant to a reactor. The tests foreseen on modules include the demonstration of a breeding capability that would lead to tritium self-sufficiency in a reactor, the extraction of high-grade heat, and electricity generation."

The remainder of the SWG-1 report outlining the design and operation requirements is given in Appendix B. Commitments by the parties to proceed to construction and a decision on selection of the construction site are scheduled for the 1998 time frame. All parties recognize the importance of ITER, both to their national fusion efforts and as an opportunity to do cooperative international science on an unprecedented scale. As recently as Fall 1996, a meeting of some sixty U.S. fusion program leaders reaffirmed support for U.S. participation in ITER and ITER's importance as an investment in fusion research, even if the U.S. participation were on the basis of a less-than-full member. There was a strong consensus that, at present U.S. fusion funding levels, continuation of the present funding level into the ITER construction phase is very well justified.

Dr. Martha Krebs, Director, Office of Energy Research at the U.S. Department of Energy (DOE), wrote to the Fusion Energy Sciences Advisory Committee (FESAC), in letters dated September 23 and November 6, 1996, requesting that FESAC review the International Thermonuclear Experimental Reactor (ITER) Detailed Design Report (DDR) and "provide its view of the adequacy of the DDR as part of the basis for the United States decision to enter negotiations" with the other interested Parties regarding "the terms and conditions for an agreement for the construction, operations, exploitation and decommissioning of ITER." The letter from Dr. Krebs provided context for the review and specifically asked that the following five questions be addressed:

1. Are the ITER physics basis, technology base, and engineering design sound? Focus on the critical physics, technology, and engineering issues that affect the design while allowing for the R&D planned in each of the areas through the end of the EDA.
2. Is ITER likely to meet its performance objectives as agreed upon by the four Parties and documented in the 1992 SWG-1 report? Evaluate predicted performance margins, comment on the range of operating scenarios, and identify opportunities to improve the performance.
3. Do the design and operating plans adequately address environment, safety, and health concerns? Focus on the methodology used by the Joint Central Team to address these concerns.

4. Are the proposed cost estimates and schedules for the construction project and subsequent operations, exploitation and decommissioning credible, and are they consistent with the procurement methods and staffing arrangements recommended by the ITER Director? Focus on the methodology used to prepare the estimates.

5. Are there any cost effective opportunities for pursuing modest extensions of the current design features in order to enhance operational flexibility and increase scientific and technological productivity of ITER? Focus on areas where cost effectiveness of any design extensions would be high.

In this Executive Summary, the Panel provides our primary findings, conclusions and recommendations. These will be given in the form of direct responses to the specific questions asked of FESAC by Dr. Krebs. We will also provide specific references to the chapters in the body of the report where a much expanded discussion is given relating both to these questions and other issues important to the ultimate success of the ITER project. The Panel did develop a significant number of other findings and recommendations relating to more specific issues, often about particular ITER subsystems. These are included in the body of the report, and often in the subpanel reports as well. The Panel and its subpanels offer these findings and recommendations to the ITER Joint Central Team (JCT) as it begins preparation of the ITER Final Design Report. For ease of reference, we repeat each question and then provide our response.

Question 1. Are the ITER physics basis, technology base, and engineering design sound? Focus on the critical physics, technology, and engineering issues that affect the design while allowing for the R&D planned in each of the areas through the end of the EDA.

Important issues in evaluating the design basis deal with the physics operation, with the new elements of the operation (burning-plasma and steady-state physics), with the technologies necessary to address these physics issues, and with the engineering design itself. Key issues include the readiness of fusion to embark on a program step having ITER's goals and the basis of confidence that ITER can reach the conditions necessary for achieving its objectives. The Panel's assessment of the physics basis for the design, and of the basis for physics-related subsystems is discussed in Chapter IV. The Panel's assessment of the engineering features of the design, specifically the likelihood that the experimental apparatus will meet its design specifications, and that it can be operated and maintained in a fashion that will meet the overall ITER program objectives, is given in Chapter V. The response we give here is repeated and expanded upon in these two Chapters.

Findings and Conclusions Regarding Question 1: The ITER Design Team has drawn widely from the world tokamak experience-base and has involved experts worldwide to produce a credible machine design. The Panel has not identified from this experience-base any insurmountable obstacles in its plasma engineering and electro-mechanical engineering that would prevent ITER from achieving its objectives. However, there are specific areas that require further attention, priority R&D, and resolution. Our overall assessment is that the ITER engineering design represented in the DDR is a sound basis for the project and for the DOE to enter negotiations with the Parties regarding construction. The subpanels noted that some aspects, such as the design of the magnet systems, are more fully developed and more mature than would normally be the case at this stage of a project. In certain other areas, such as the first wall and the bolted blanket/shield approach, it is not yet clear whether the present design can meet its performance requirements, and focused efforts are underway to develop final designs. A theme throughout the subpanel recommendations is a need for formal, quantified reliability, availability, and maintainability (RAM) requirements and analyses. The subpanels noted a number of other areas that will need focused R&D and detailed design efforts in the post-EDA period.

Question 2. Is ITER likely to meet its performance objectives as agreed upon by the four Parties and documented in the 1992 SWG-1 report? Evaluate predicted performance margins, comment on the range of operating scenarios, and identify opportunities to improve the performance.

ITER is clearly of the scope and scale required to explore extended-pulse, self-heated fusion plasma physics. However, in assessing ITER's anticipated performance, it is important to do so in the context of ITER as a scientific experiment — the first attempt at magnetic fusion ignition and controlled burn. In particular, to reach its peak performance, ITER will extend issues such as confinement, pulse-length and alpha-heating effects far beyond those attained in present-day tokamaks. As such, predictions for its performance cannot be made precise, given the experimental nature and goals of the ITER program. The best that can be given are predictions of most probable performance, together with the associated uncertainty, for each of the individual aspects and hence for ITER as a whole. In the end, the judgment that must be made, as with any scientific experiment, relates to the balance between design risk and design conservatism, given the present state of knowledge and the objectives and goals of the experiment. The findings and conclusions presented next are expanded upon in Chapter VI.

Findings and Conclusions Regarding Question 2. In the Panel's estimation, based on extrapolated tokamak confinement data, the expected performance of ITER's base operating mode (ELMy H-mode confinement) ranges from that of fusion ignition ($Q \infty$) to a moderately self-

heating burning plasma ($Q \sim 4$). (Here Q is the ratio of fusion power produced to energy input to sustain the plasma.) There is high confidence that ITER will be able to study long pulse burning plasma physics under reduced conditions ($Q \gtrsim 4$), as well as provide fundamental new knowledge on plasma confinement at near-fusion-reactor plasma conditions. Achieving long pulse ignition cannot be assured, but remains a reasonable possibility. The Panel concludes that the DDR incorporates significant flexibility within the design and costs constraints, through multiple options to explore combinations of heating, fueling, shaping, and current drive control. Additional analysis is called for to insure adequate flexibility to access advanced confinement regimes. The Panel also recommends that flexibility for additional heating power be made available in case it is needed to provide adequate neutron wall loading, as well as adequate plasma stored energy (beta) and power flow across the separatrix. This will give confidence of access to the H-mode, as well as permit ITER to achieve the necessary physics and technology tests, even if the plasma performs near the low end of its predicted confinement range. To assure the upgradability of the heating and current drive systems to approximately 200 MW (if needed), the design team should carefully assess the implications for port space, auxiliary areas, and site power.

The Design Team has focused its attention and resources so far primarily on successful operation in the Basic Performance Phase, with the view that the knowledge and experience gained in this phase will guide the Enhanced Performance Phase. Consequently, achieving the Basic Performance Phase objectives looms large in the DDR design, and the Enhanced Performance Phase objectives have not been addressed beyond assuring capability of the facility to address those objectives. The Panel concurs with this approach.

Question 3. Do the design and operating plans adequately address environment, safety, and health concerns? Focus on the methodology used by the Joint Central Team to address these concerns.

ITER is a large and complex device which will use tritium as a fuel and produce energetic neutrons as an output. Careful tracking and control of the tritium inventory will be required and in this connection, removal of tritium from the first wall of the vessel remains an outstanding issue. As a result of neutron bombardment, the machine structure and surrounding materials will become activated. The ITER device will require a nuclear license to operate wherever it is sited, yet is unlike any other device that has been licensed previously. Detailed safety requirements have been established based on recognized international safety criteria. These limits are not always as restrictive as U.S. limits, but upgrading the design to meet U.S. regulations is not a fundamental concern. Safety requirements have been an integral part of the overall design requirements. Careful analysis has been done to show that the facility will operate within these requirements in both normal and accident

scenarios. These analyses have been carried out using the best available understanding and computer codes. The project has, as a design requirement, the avoidance of the need to evacuate the general public following the most serious accident. A general project objective is that the dose to workers and the public be maintained as low as reasonably achievable (ALARA). The findings and conclusions presented next are expanded upon in Chapter VII.

Findings and Conclusions Regarding Question 3. The ITER team has an appropriate organization in place to address nuclear issues and has, in general, addressed these issues in an appropriate manner. The nuclear design effort has been the subject of a recent review by the four parties within the ITER framework and the work done has been documented in the Non-site Specific Safety Report (NSSR-1). The safety aspects of the design and analysis are adequate for this stage of the project.

Question 4. Are the proposed cost estimates and schedules for the construction project and subsequent operations, exploitation and decommissioning credible, and are they consistent with the procurement methods and staffing arrangements recommended by the ITER Director? Focus on the methodology used to prepare the estimates.

The cost and schedule development process used by the JCT is based on a detailed set of procedures and formats that facilitated a standardized and consistent cost and schedule estimate. For many components, and for virtually all of the tokamak components, industrial estimates have been obtained from multiple Parties (herein to be understood as industries of those Parties) in preparation for the Interim Design Report (IDR). For some components, estimates were obtained from a single Party, and for buildings, diagnostics, and machine tooling they were internally generated by the JCT. The IDR Cost Estimate represented a bottoms-up estimate of almost every element of ITER. The cost and schedule issues are discussed in greater detail in Chapter VIII.

Findings and Conclusions Regarding Question 4. In the Panel's judgment, the JCT has done a disciplined and thorough job in gathering the complex data from diverse parties and developing a self-consistent cost and schedule data-base predicated on sound cost and schedule estimating methodologies. Estimates for components and systems are primarily based on industrial estimates from multiple parties, and have been extensively analyzed and processed to insure credibility, completeness and accuracy. Overall, the Panel judges the cost estimate to be reasonable and sound for this stage of the project. The Panel does note that the plan is a success-oriented one, in that there is little or no budget or time allotted to accommodate unforeseen problems that may arise. An efficient management structure and procurement system, taking maximum advantage of industrial

competition in bidding, is required during construction to meet the aggressive cost and schedule goals of the project.

Question 5. Are there any cost effective opportunities for pursuing modest extensions of the current design features in order to enhance operational flexibility and increase scientific and technological productivity of ITER? Focus on areas where cost effectiveness of any design extensions would be high.

The ITER design is a complex one and the Panel is well aware of the time and effort needed to determine if any design suggestion, either for modification or extension, is one that can meet the design requirements and system specifications established to ensure the credibility of the engineering design itself. Given this, and given the short time available to the Panel to conduct this review, the Panel has chosen not to focus on this question. However specific suggestions are included in the bulk of the panel report, and in the appendices - especially in the area of flexibility - which we think are worthy of careful review by the ITER team. Indeed many of these are already under study by the ITER Joint Central Team and the various Home Teams.

In closing, the Panel would like to re-affirm the importance of the key elements of ITER's mission - burning plasma physics, steady-state operation, and technology testing. The Panel has great confidence that ITER will be able to make crucial contributions in each of these areas. While we have identified some important technical issues, we have confidence that the ITER team will be able to resolve these issues before the Final Design Report (FDR). Furthermore, even in the unlikely circumstance that the ITER plasma performs at the lower end of its predicted range, heating and current drive upgradability to ~200 MW would provide greater confidence that ITER will be able to fulfill its programmatic role. The achievement of ITER's mission will be a major milestone in the development of a safe, economic, and sustainable energy source for the future.

II. Background: The Role of ITER in the World and U.S. Fusion Programs

The objectives for ITER are “...to demonstrate controlled ignition and extended burn ...,” “...to demonstrate steady-state operation...” and “...to demonstrate the technologies essential for a fusion reactor...” ITER consequently brings together three threads important for fusion advancement and it will be a testbed for key scientific and technological elements central to the achievement of a fusion power system.

The President's Committee of Advisors on Science and Technology (PCAST) reiterated in 1995 the importance to fusion of achieving strongly self-heated plasmas in the laboratory, i.e., the production and exploration of a plasma that is heated by its own charged reaction products and as such, requires little or no external sources of heat. The burning state of plasma operation is characterized by the plasma power amplification factor, Q , defined as the ratio of the fusion power to the external source of input power to the plasma. An ignited plasma is characterized by a Q value of infinity. For a plasma fueled with deuterium and tritium, the point $Q = 5$ is a system in which the fusion plasma self-heating power from alpha particles equals the external source of plasma heating power.

Although much of the burning plasma physics can be learned through self-heated plasma experiments in short-pulse machines, and several devices to accomplish this have been proposed, ITER's objective is to demonstrate that high- Q operation can be sustained for time-scales long compared to natural time-scales of the plasma fuel and ultimately to achieve “steady state.”

The combined physics objectives for ITER introduce engineering and technology demands far exceeding those of predecessor facilities, e.g., fully superconducting magnets for plasma confinement, systems to operate and handle both high-power heat and neutron loads, a machine that is remotely maintained, and a machine capable of testing the breeding of tritium in high-temperature blankets prototypical of those needed to produce electricity. Hence, the development of the enabling fusion power technology becomes an objective in its own right.

The physics objectives of ITER have been broken into two phases of operation. The first phase, the Basic Performance Phase (BPP), is intended to explore burning-plasma physics in moderate-pulse (~ 1000 s), inductively-driven discharges. This operation will study and document operating characteristics that today can only be modeled for a reactor scale tokamak, e.g., energy confinement, divertor performance, plasma-wall interactions and alpha particle physics. Most of the

attention of the ITER Joint Central Design Team (JCT) has to date been focused on meeting the objectives of this phase while preserving flexibility to address the second.

The second phase, the Enhanced Performance Phase (EPP), will address driven-current steady-state and advanced modes of operation, pointing towards the 1 MW-yr/m² fluence objective. Preparations for this phase will be based on lessons learned in the BPP and will likely require modifications of internal hardware.

In the view of the Panel, ITER will be considered a scientific success if in the BPP it demonstrates strong self-heating (say, $Q \sim 10$) of a long-pulse D-T plasma, although this will be a significant technological achievement as well. ITER will be considered a technological success if in the EPP it demonstrates reliable operation for an extended period (say, ~ 10 years) with a neutron fluence of ~ 1 MW-yr/m². These successes would represent major steps toward demonstrating the scientific and technological feasibility of fusion energy. Together with further improvements in plasma performance and plant availability, ITER will provide critical information required for the design of an attractive fusion DEMO power plant.

Prior to ITER, the importance of burning-plasma physics issues led to separate activities to design facilities that would operate in the U.S., Europe, Japan and Russia, albeit with differing emphases regarding technical details, pulse lengths, etc. The projected costs made it unlikely that any one national party would be willing or able to support such a step fully on its own, and certainly made it unlikely that more than one such machine would be built. Joining together became a step that built naturally on fusion's long and successful history of international cooperation, even though there would be complications introduced by a multi-national effort. With each of the four partners at a roughly equivalent stage of fusion development (itself partially a product of cooperation), equality of participation became a natural organizing principle. With the agreement that all information would be shared among the partners, each would be assured an immediate multiplier on its ITER investments. Taken as a whole, the resulting partnership to share in a facility exploring burning plasma physics created a unique opportunity to advance fusion science.

Against this background, the ITER design effort was established as a truly internationally managed project, comprising equal partners but recognizing the need for project lines of authority. The Terms of Reference and the Management Plan were developed through four-party negotiations and laid out the plan for the phased operation described above. The design and supporting R&D phase (which is all that has been committed to so far by the partners) was divided into two parts, a

Conceptual Design Activity (the CDA) and an Engineering Design Activity (the EDA), each of which would be reviewed by the partners.

The CDA phase, completed in 1991, determined the broad features of the facility required to address ITER's objectives, made a first estimate of the cost, identified critical issues, and established the R&D requirements to be carried out in the subsequent phase.

The EDA phase was formally established by the ITER-EDA International Agreement in 1992 and is to be completed in July, 1998. Three coordinated centers for the JCT were created in the U.S., Europe and Japan, the seat of the ITER council was set in Russia, and a Director was appointed. The EDA was to address non-site-specific aspects of the design, develop detailed engineering designs, conduct component prototype R&D and testing, and ultimately be responsible for providing the design acceptable by the parties for entering into construction. Site-specific aspects of the design were to be carried out after the formal end of the EDA period. Some design work and most supporting R&D were to be carried out through Home Teams of each of the partners, with coordination with the JCT. Multi-national expert groups were established to advise the JCT on the physics basis for the design.

The general objectives and the plasma performance and engineering performance objectives established at the beginning of the EDA Phase for ITER are set out in the report of the Special Working Group-I (SWG-I) (See Appendix B). In short, these objectives are:

General Objectives

“The ITER detailed technical objectives and the technical approaches, including appropriate margins, should be compatible with the aim of maintaining the cost of the device within the limits comparable to those indicated in the final report of the ITER CDA as well as keeping its impact in the long-range fusion programme. ITER should be designed to operate safely and to demonstrate the safety and environmental potential of fusion power.”

Plasma Performance Objectives

“ITER should have a confinement capability to reach controlled ignition. The estimates of confinement capability of ITER should be based, as in the CDA procedure, on established favorable modes of operation. ITER should demonstrate controlled ignition and extended burn for a duration sufficient to achieve stationary conditions on all time scales characteristic of plasma processes and plasma wall interactions, and sufficient for achieving stationary conditions for nuclear testing of blanket components. This can be fulfilled by pulses with flat top duration in the range of 1000 s. For

testing particular blanket designs, pulses of approximately 2000 s are desirable, with the ultimate aim of demonstrating steady state operation using non-inductive current drive in reactor relevant plasmas.”

Engineering Performance and Testing Objectives

“ITER should demonstrate the availability of technologies essential for a fusion reactor (such as superconducting magnets and remote maintenance); test components for a reactor (such as exhaust power and particles from the plasma); and test design concepts of tritium breeding blankets relevant to a reactor. The tests foreseen on modules include the demonstration of a breeding capability that would lead to tritium self-sufficiency in a reactor, the extraction of high-grade heat, and electricity generation.”

Commitments by the parties to proceed to construction and a decision on selection of the construction site are scheduled for the 1998 time frame. All parties recognize the importance of ITER, both to their national fusion efforts and as an opportunity to do cooperative international science on an unprecedented scale. As recently as Fall 1996, a meeting of some sixty U.S. fusion program leaders reaffirmed its support for U.S. participation in ITER and ITER's importance as an investment in fusion research, even if the U.S. participation were on the basis of a less-than-full member.

III. DOE Charge to FESAC and the Committee's Process and Procedures

Statement of the Charge

Dr. Martha Krebs, Director, Office of Energy Research at the U.S. Department of Energy (DOE), wrote to the Fusion Energy Sciences Advisory Committee (FESAC), in letters dated September 23 and November 6, 1996, requesting that FESAC review the International Thermonuclear Experimental Reactor (ITER) Detailed Design Report (DDR) and “provide its view of the adequacy of the DDR as part of the basis for the United States decision to enter negotiations” with the other interested Parties regarding “the terms and conditions for an agreement for the construction, operations, exploitation and decommissioning of ITER” (the letters are included in Appendix C). The letter from Dr. Krebs provided context for the review and specifically asked that the following five questions be addressed:

1. Are the ITER physics basis, technology base, and engineering design sound? Focus on the critical physics, technology, and engineering issues that affect the design while allowing for the R&D planned in each of the areas through the end of the EDA.
2. Is ITER likely to meet its performance objectives as agreed upon by the four Parties and documented in the 1992 SWG-1 report? Evaluate predicted performance margins, comment on the range of operating scenarios, and identify opportunities to improve the performance.
3. Do the design and operating plans adequately address environment, safety, and health concerns? Focus on the methodology used by the Joint Central Team to address these concerns.
4. Are the proposed cost estimates and schedules for the construction project and subsequent operations, exploitation and decommissioning credible, and are they consistent with the procurement methods and staffing arrangements recommended by the ITER Director? Focus on the methodology used to prepare the estimates.
5. Are there any cost effective opportunities for pursuing modest extensions of the current design features in order to enhance operational flexibility and increase scientific and technological productivity of ITER? Focus on areas where cost effectiveness of any design extensions would be high.

Context for the Panel's Work and Charge

In responding to the charge and these questions, the Panel took account of three important aspects of the context in which the questions have been posed: the status of the design, the international partnership, and the role of ITER as a fusion science experiment.

The EDA phase will not end until 1998, and some important R&D activities will continue even beyond that time. Thus the design is still evolving, and therefore the Panel's assessment is necessarily one made at a time when the design is still ongoing. In fact we hope issues raised both by the Panel and the subpanels will assist in the ongoing design activity. (Many issues raised here will be adequately dealt with in the FDR, and should not be viewed as impediments.)

With respect to the international context, it is clear that full partnership in the form of the U.S. providing 25% of the ITER construction cost is unlikely, given the present level of funding for fusion energy research in the United States. A more likely scenario is that we will participate in a more limited way that depends on our available funding, though this clearly depends on unfinished negotiations with the other Parties. We do note that our present contributions to the ITER EDA are \$55 million per year, or about 25% of the U.S. fusion program budget. We attempt in our review to address the broad issues facing ITER without regard to who actually funds and constructs the experiment. In the end, it will be the host of the actual ITER facility that will make the primary determination about the achievability of the goals (risk vs. reward) in the context of their own national science and technology policy.

Finally, regarding the role of ITER as a fusion science experiment, the Panel draws a distinction between the need for a robust experiment and its performance in terms of results ultimately achieved. We believe it to be essential that the design represent a robust facility in terms of plasma engineering (plasma position control, volt-seconds adequate for 1000-sec pulses, etc.) and electrical/mechanical engineering (magnet design, remote maintenance, etc.). Physics performance, on the other hand, is difficult to guarantee since ITER, even though it makes important contributions to fusion technology, is a major fusion plasma science experiment. This perspective has become increasingly clear during the past decade of ITER design activity. Therefore, we are not overly concerned that questions exist about high Q vs. ignited plasma operation, about helium ash buildup, and other similar questions since these are just the issues that will be resolved by doing the experiment. What is important is that the machine be designed with the capability to address these key physics questions.

Review Process

The ITER Joint Central Team (JCT) issued an Intermediate Design Report (IDR) in 1995, and issued a Detailed Design Report (DDR) in December 1996. The Final Design Report will be issued in 1998. The DDR is a supplement to the IDR. Since neither FESAC nor its predecessor committee,

FEAC, reviewed the IDR, it was determined that both the IDR and DDR would be reviewed as part of the current process.

Following receipt of the charge letter from Dr. Krebs, this Panel, consisting mainly of FESAC members, was formed and charged by FESAC with overall responsibility for the review. The chair of FESAC and the chair of the Panel formed in turn a number of subpanels, each charged to review particular elements of the ITER design reports. The membership of the Panel and the nine subpanels, together with the dates of their various meetings, are given in Appendix A. The subpanels included FESAC members, numerous outside experts and a broad representation of people from the fusion community. The formation of the subpanels provided the Panel with the means to hear from and include outside experts, and the means to insure the broad representation of the fusion scientific and technical community in the review. The chairman of FESAC determined that FESAC members who were employed primarily on ITER activities should not participate in the preparation of the subpanel reports, but should participate to provide clarifying information. None of the members of the Panel are employed primarily on ITER activities.

The review was handled by an iterative procedure. First, the contents of the IDR and DDR reports were divided by topic and sent to the subpanels, who were asked to review their assigned areas. To assist in this process, the U.S. ITER Home Team provided a brief review of several major areas. On January 21 and 22, 1997, the FESAC and subpanel chairs met at General Atomics in San Diego and heard extensive presentations on the status and prospects for the project from key ITER Joint Central Team personnel.

The FESAC was impressed by both the depth of the R&D and the analysis performed in support of ITER, and by the enthusiasm and excitement for the project exhibited by the members of the ITER Team. This is a true tribute to Dr. Robert Amyar, Director of the ITER JCT, and his management team. In addition, the FESAC heard valuable public comment from a number of people. The agenda of the meeting and names of presenters is provided in Appendix A.

Following this meeting, the Panel and its subpanel chairs met to discuss initial reactions to the ITER reports and presentations, to formulate questions and to ask for clarifications as soon as possible. We also agreed to the process for completing the review and preparing the Panel report. The subpanels carried out reviews and prepared reports for the Panel and these are included here as Appendix D*. The subpanel reports, along with the ITER IDR and DDR and the presentations by the ITER team, formed the primary source material that have informed the Panel's deliberations.

The Panel met for a second time at the University of California, San Diego on March 20th and 21st to prepare the report you see here. The final version was completed after various iterations during the next two week period. We express our sincere thanks to the ITER team and its Director, Dr. Robert Amyar, for all their work. We also thank all those who worked so hard under a trying time schedule to complete the subpanel reports. In the end, however, this report and its findings, conclusions and recommendations are those of the Panel alone. We trust the reader finds diligence in our efforts.

*Appendix D: Sub-Panel Reports

- Appendix D.I: Physics Basis Report
- Appendix D.II: Heat Flux Components, Fuel Cycle
- Appendix D.III: Report on Disruptions/VDES and Blanket/Shield Attachment
- Appendix D.IV: Advanced Modes, Flexibility, and Heating
- Appendix D.V: Operability and Safety
- Appendix D.VI: Magnet Report
- Appendix D.VII: In-Vessel Components
- Appendix D.VIII: ITER Cost and Schedule Assessment
- Appendix D.IX: Facilities

IV. Assessment of the Design Basis

Important issues of the design basis discussed in this Section deal with the physics operation, with the new elements of the operation (burning-plasma and steady-state physics), and with the technologies necessary to address these physics issues. They involve the readiness of fusion to embark on a program step having ITER's goals and with the basis of the confidence that ITER can reach the conditions necessary for achieving its objectives. The supporting engineering design basis is discussed in Section V. The major finding of this section, which provides part of our answer to the first question asked by Dr. Krebs is:

Finding and Conclusion: *The ITER Design Team has drawn widely from the world tokamak experience base and has involved experts worldwide to produce a credible machine design. The Panel has not identified from this experience base any insurmountable obstacles in its plasma engineering and electro-mechanical engineering that would prevent ITER from achieving its objectives. However there are specific areas that require further attention, priority R&D, and resolution.*

PHYSICS BASIS

The ITER design builds on the research results of all the world's major tokamaks and their predecessors, and, in recent years, it has been a driver of this research. The development of successful operating modes in all these tokamaks augurs well for developing favorable modes in ITER, also. As a group, these tokamaks have advanced fusion research to the brink of break-even plasma conditions, seen in the production of multiple megawatts (MW) of fusion power in deuterium-tritium operation together with the first studies of alpha-particle physics. They have explored new operating modes that reduce ion thermal transport to its neo-classical level and have seen the use of increasingly sophisticated diagnostic instruments to measure the internal quantities necessary for detailed testing of theoretical models.

A. Equilibrium, Stability and Dynamics

Large-scale plasma behavior is dominated by ideal-MHD phenomena, but it also includes important resistive (non-ideal) effects. Ideal-MHD behavior is one of the most mature and best understood areas of fusion science. Based on an experience base developed worldwide, complex codes now calculate plasma equilibria, evolution and stability; and detailed plasma diagnostics confirm these calculations in a predictable and reliable manner.

The picture is less mature and to some extent remains empirical for dissipative phenomena leading to island growth, magnetic tearing, sawteeth and disruptions. However, there has been and continues to be much progress in understanding the basic processes, the structure of unstable modes and their non-linear behavior. Disruptions of the current channel present a special issue for ITER, as they can arise from a variety of causes and they become more common in high-performance conditions like higher-beta operation. Also, the tokamak experience base provides little information regarding the disruption likelihood, or frequency, in long-pulse conditions. Techniques for limiting or otherwise dealing with disruptions and other dissipative phenomena are now being tested, or are to be tested in the near term.

There is therefore a good basis for confidence of achieving the plasma necessary to carry out the more refined studies on aspects for which the physics models are not so mature, e.g., that the actual limiting pressure will likely be a “soft-limit” set by dissipation, or how the disruption frequency will depend on operating conditions or be manifest in the extended ITER pulses. R&D priority should be given to the issues of neo-classical-resistivity-driven island formation, including ECH or other techniques for their elimination; and given to continued ongoing studies of disruption frequency, severity, current distribution, runaway-electron formation, etc., including techniques for avoidance, anticipation or mitigation.

B. Confinement, Transport and Turbulence

The issue of energy confinement has central importance for ITER's goal of exploring burning-plasma physics and/or achieving full, self-heated ignition. The “ELMy H-mode” regime of confinement called for in ITER's base operation and the conditions for achieving it have been well documented, and the underlying mechanisms for its generation are coming to be well understood. New to ITER will be the effects of increased size and power and the requirement to hold this condition for an extended duration.

Although considerable progress has been made in recent years understanding and modeling the effects of fine-scale electric-field turbulence, a first-principles approach to predicting confinement behavior of ITER is not generally considered as reliable today as extrapolation from current experiments, for which two independent approaches are being used. The first is a statistical extrapolation based on a data base drawing on the past and current performance of all the world's tokamaks. This technique yields an ITER confinement-time prediction with a $\pm 50\%$ uncertainty, corresponding to a range of gain from ignition down to $Q \sim 4$. The second approach uses “dimensionally equivalent” discharges in current tokamaks and tends to bear out the statistical

projections. These discharges are an attempt to simulate ITER in shape, profiles, etc., and in many plasma dimensionless parameters except, notably, the size measured in gyroradius. Applicability of the sole plasma-physics-based non-dimensional scaling method is limited because of the closeness of the ITER operating point to the H-mode threshold and the Greenwald density limit (n_G); as a consequence, there is uncertainty as to whether the scaling in ρ^* (ratio of gyroradius to machine size) can be extended from present machines to ITER.

Theoretical and experimental indications that edge conditions may profoundly affect the core temperature (and thus ignition) demand further investigations. High priority should be given to studies of edge-physics, including development of techniques for extrapolation to ITER conditions. It will also be important to continue developing and benchmarking theoretical and computational tools for predicting all aspects of confinement, together with exploring means for optimizing performance within each confinement model. Progress in this area has been very good recently, both in experiments and theoretical understanding.

C. Plasma-wall Interactions

ITER's divertor is an important element in the interaction of the plasma with material structures and is key to ITER's achieving its objectives. Because of the high thermal power, the divertor must operate in a mode in which the lost power is dispersed through radiation over the areas adjacent to the divertor strike-plate. The physical processes operative in the divertor region are largely well understood. At issue are the interplay of plasma, atomic and surface physics phenomena and the optimization of baffling that simultaneously achieves high radiative-power fraction and high plasma performance.

Several tokamaks are currently exploring radiative divertors and benchmarking computational models, with noteworthy successes. On the basis of these studies, there is reason to have confidence that the ITER divertor can handle its power and particles in the BPP. However, there remain many issues associated with combining the divertor needs with those of a high-performance plasma. Because of the importance of the divertor in high-power fusion plasma operation, ITER is designed to permit reconfiguration of the divertor as improvements emerge. It will be important to continue the supporting research on divertor chambers matching the current and new divertor designs.

D. Wave- and Particle-plasma Interactions

Through the course of its operations, ITER is expected to employ neutral beam, radio-frequency and microwave heating in developing optimized paths to nuclear self-heating. Fueling will be accomplished by gas feed, pellet injection, and (perhaps later) compact-tori (CT) injection. The physics bases for most techniques for heating and fueling plasmas are well established, and the computational tools for modeling these processes are mature and thoroughly benchmarked. Other techniques, like CT injection, are more speculative and require investigation in current machines.

E. Burning-plasma Physics

Exploration of potential alpha-particle-driven instabilities and the effects of strong alpha self-heating on plasma profiles are primary objectives of ITER operation. The single-particle behavior of fusion-alpha particles has been explored in TFTR (and will be explored further in JET) with the result that under its conditions the alpha orbits, loss, slowing down, etc., are largely classical. Modes of collective alpha-particle behavior predicted to occur under higher alpha pressure have been simulated under using DT alphas in TFTR and other energetic ions in deuterium plasmas. Many of these experimental results have behaved in accordance with theoretical predictions. As a consequence, there is good reason to believe that alpha particles will normally be well confined in ITER.

ENGINEERING AND TECHNOLOGY

Accomplishing the ITER objectives relies on successful operation of a large number of systems. Many of these employ current technologies developed in other fields; others are unique to fusion research and use technology developed within the world fusion program. Overall, the level of development of the relevant technologies is sufficient for proceeding with ITER. Further R&D is needed in some cases, but there is sufficient time to do the R&D needed to demonstrate a particular level of capability, provided it is given sufficient priority. Furthermore, in most areas, the flexibility exists to replace components with improved designs or materials, and a number of alternatives are available.

A. Magnets and Magnetism

The magnetic systems are unique to ITER in size, configuration, loads (mechanical and thermal), and construction detail, although there is a good experience base in Tore Supra and the LHD. In recognition of the need to meet specifications and provide extraordinary reliability, an extensive development and prototype demonstration program has been mapped out and is under way. The cable-in-conduit magnet construction has been used in smaller systems, as have the techniques proposed for dealing with both normal and off-normal mechanical and thermal loads. However, it is crucial that the plan for building and testing prototypes be carried out in a rigorous and timely fashion.

The magnetism design, i.e., the specification of the sizes, locations, and capabilities of each coil, is based on extensive experience throughout the world on developing the coil requirements for high performance, shaped plasmas (JET, JT-60U, DIII-D, Alcator C-Mod and TPX design). The requirements for shaping the ITER plasma, inductively driving the plasma current, controlling the plasma during transient conditions, and accommodating large plasmas transients, draw on an extensive tokamak base. The related power systems are straightforward but require substantial extensions.

B. Divertor, Particle and Heat Removal

The lifetime of the ITER divertor is affected by issues such as erosion, tritium inventory and immobility, and thermal and mechanical loads during disruptions. The divertor also has to control the recycling and removal of particles from the chamber. Key design questions are the configuration of the divertor—open, closed, slotted, baffled—and the materials, attachments, and heat removal systems

for the high heat flux zones. Extensive work on a wide variety of configurations has been carried out using the major present world tokamaks. The use of slots allows an increased area for collection of plasma heat while permitting control of particle recycling. The ability to remove and replace divertor cassettes as operating experience develops is a key ITER design goal. The program in high heat flux materials and development of reliable attachments is an on-going R&D effort.

C. Heating and Current Drive (H&CD) Systems

All of ITER's H&CD systems have been objects of development for fusion applications for several decades. However, applying these techniques to the ITER needs will require special development. ITER will use a variety of systems, including neutral beams, ion cyclotron RF (ICRF) frequency and electron cyclotron heating (ECH) systems, and possibly a lower hybrid frequency RF system. High energy neutral beams based on negative ion sources are being developed for and installed in a 500 keV system on the JT-60U tokamak. Prototype ITER systems have been operated at above 900 keV on test stands and their development is continuing. The principal ICRF question is the development of the antenna structure, which is unique to each tokamak and for which special materials will be required in ITER; other components make use of well developed RF technology. ECH depends on the development of a continuously operating high-frequency (170 GHz) gyrotron source which is the subject of active R&D extending lower-frequency techniques.

D. Diagnostics and Instrumentation

Many diagnostic measurements will be required to operated and reap the benefits of ITER. Both its routine operation and experiments require extensive instrumentation of the plasma, the tokamak hardware, and the modules needed for engineering and technology tests. Further, the mission places high emphasis on neutron diagnostics. ITER's unique feature is the radiation environment in which all the plasma diagnostics and the instrumentation of components close to the plasma will have to operate. TFTR has provided useful experience for dealing with these issues, and JET continues to do so.

E. Fueling and the Fuel Cycle

The TSTA tritium project at LANL and the tritium systems for TFTR have worked even better than anticipated, and have provided a good experience base for design of the ITER tritium system. JET continues contributing directly relevant tritium experience. ITER expects to rely on gas injection supplemented by injection of solid pellets having shallow penetration; both are familiar in tokamak

operation. ITER's special fueling issues are its size and the need for deep fueling; high-field launch is a new technique to achieve this and will be tested soon. Although conditioning of the walls has been a part of the operation of every tokamak, the experience base is for pulsed tokamaks. Development and optimization of wall conditioning techniques for long-pulse operation must be considered part of the initial operating plan.

F. Vacuum, Cooling, Cryogenics, Thermal Shielding

Although the sizes and configurations of these components are unique to ITER, the underlying technologies are well developed and widely used. These mechanical, structural, and thermal components are to be constructed of familiar materials (e.g., 316LN stainless steel). Codes of good engineering practice provide detailed guidance to the engineers.

V. Assessment of Construction, Operation, and Maintenance

The current understanding of Tokamak physics and reasonable extrapolations of key technologies have been used to determine the basic machine parameters and high level system/subsystem specifications, as discussed in the previous section. In this section, we summarize the results of our assessment of the engineering features of the design. That is, is it highly likely that the implementation of this design will follow according to the overall project plan, that the experimental apparatus will meet its design specifications, and that it can be operated and maintained in a fashion that will meet the overall ITER program objectives?

As described earlier, our assessment was carried out mainly through a set of subpanels that concentrated on specific aspects of the ITER program and the design. The subpanels most relevant to this section are Magnets, In-Vessel Components, Facilities, and Operability and Safety. Assessments by the other panels relating to the engineering readiness and robustness of the design, especially regarding the envelope of the engineering systems performance needed to cover the interesting physics regimes, were included.

Finding and Conclusion: *The Panel's overall assessment is that the ITER engineering design represented in the DDR is a sound basis for the project and for the DOE to enter negotiations with the Parties regarding construction. The subpanels noted that some aspects, such as the design of the magnet systems, are more fully developed and more mature than would normally be the case at this stage of a project. In certain other areas, such as the first wall and the bolted blanket/shield approach, it is not yet clear whether the present design can meet its performance requirements, and focused efforts are underway to develop final designs. A theme throughout the subpanels recommendations is a need for formal, quantified reliability, availability, and maintainability (RAM) requirements and analyses. The subpanels noted a number of other areas that will need focused R&D and detailed design efforts in the post-EDA period.*

In any cutting edge high technology endeavor like ITER, considerations of proposed modifications in the hardware design will arise as the detailed designs are completed, and as results from the physics and technology R&D programs come in from ITER and elsewhere. Balancing technical risk with a need to maintain the cost and schedule constraints on the project will require single point leadership and decision making to maintain our present confidence that the machine will meet its engineering specifications and its operational and maintainability requirements. This is a formidable challenge in any large scale, highly visible project on the scale of ITER, and the need to

maintain a consensus among the international multi-party shareholders adds significantly to these challenges.

A theme throughout the subpanel recommendations is a need for formal, quantified reliability, availability, and maintainability (RAM) requirements and analyses. Availability goals need to be established as early as possible and allocated to each system, sub-system, and component. While some detailed calculations of mean-time-to-failure have been performed as part of the safety analyses, and some difficult issues associated with remote handling have been considered in detail, in most cases a standard does not exist to judge if a system has met its objectives.

MAGNETS

Overall, the magnet subpanel was impressed with the detail presented in the material made available to them and they feel that the design team has progressed on schedule towards a final design that will meet or exceed the engineering requirements of the General Design Requirements (GDR).

A. Coil Subsystem: The design at the present stage of development is well conceived, presented and laid out. Specific areas requiring further emphasis are the model coils, the conductor strand, and cable and joint testing. There has been a non-trivial erosion of the Model Coil schedules during the past year and significant reduction of smaller R&D programs supplying data to the design effort. Data from the Model Coil Programs (fully verified and understood by all Parties) will probably not be available until mid to late 1999 for the CS and mid to late 2000 for the TF magnets. This is a success oriented schedule with no allowance for significant problems emerging in any of the coil tests.

Adequate performance of conductor strand has been well established. In contrast to strand testing, testing to date on full-scale cable and joints has not been sufficient. Tests on subsize cables indicate that adequate performance can be expected, although there are large variations in AC losses that are not completely understood.

B. Cryostat: This system provides the vacuum and thermal insulation for the superconducting magnets and forms part of the radiological secondary containment. The design is well supported by a comprehensive analytical effort, and it should meet its specifications. A quantized reliability/availability assessment is needed to evaluate and guide the design, with special attention to the numerous bellows and penetrations into the cryostat..

C. Coil Power Supply and Distribution System: The DDR power supply design uses conventional technology and it should meet the requirements imposed on it by the basic coil parameters and ITER operating scenarios.

IN-VESSEL COMPONENTS

Overall the In-Vessel systems have benefited from a great deal of innovative engineering. The subpanel identified several areas of potential risk that would benefit from a focused effort during the remainder of the Engineering Design Activity:

First, the failure rate of blanket modules may be unacceptably high causing the machine to have low availability. An in-depth failure analysis that recognizes potential modes should be conducted. Attention should be paid to the rapid detection (including location) of leaks. Particular areas of concern include the copper to stainless steel bond on the first wall heat transfer surface, the many welded joints and the insulator integrity in the bolted module.

Second, the present bolted blanket/shield design appears marginal for the EM disruption loads that have been analyzed so far. The ongoing efforts should aim at a design that can withstand at least 500 full power disruptions.

Third, the assembly tolerance requirements are extremely demanding. Their realization will depend on having a capable optical metrology system, tooling to position heavy components accurately, and adequate support structures to keep components from shifting after assembly. These are all receiving appropriate consideration but the capabilities will need to be demonstrated in advance to be convincing.

Lastly, the consequences of a failure in the remote maintenance system and the procedure for recovery should be analyzed to avoid a potential long delay once machine operations have begun.

FACILITIES

An objective in laying out the facilities of ITER was to try to avoid, wherever possible, the crossing of different services such as electrical power, cooling water, and waste handling. To achieve this objective, the ITER project placed the tokamak in a pit in the center, with the various support buildings radially located to the north, south, east, and west. A lot of time and thought went into designing the tritium handling and waste treatment facilities. The design has built upon the experience

gained from fusion experiments that handle tritium as well as fission reactors, which must deal with radioactive waste streams. The ITER project appears to have done an excellent job in both of these areas.

OPERABILITY AND SAFETY

Machine Operability: ITER has the potential to operate effectively and achieve its program goals. No concerns were identified which would *a priori* preclude this. However, a number of areas must be addressed in greater depth by the ITER team before one can say with confidence that their operational goals will be achieved. The formation of a group that would take responsibility for operations related issues of the design, including assuring that the facility will be able to meet its reliability and availability goals, would facilitate the resolution of these issues..

The total number of pulses allocated for operation during the basic performance phase (BPP) would significantly limit the scope of the research and technology program. The Panel suggests that an increase to 30,000 to 50,000 shots during the BPP (10 years) from the present requirement of 15,000 shots be evaluated.

The availability of ITER and related goals are defined in the DDR in a manner which is difficult to interpret and implement. A better definition is shots completed divided by shots planned, and an appropriate goal would be 80-90% in the last years of the BPP.

Proper wall conditioning has been crucial to good tokamak operation. New techniques need to be developed for ITER because the toroidal field isn't turned off between discharges, in contrast to present day Tokamaks. The ITER Project should fully define the techniques to be used for wall preparation and consider increasing the baking temperature to 300 C.

A. Plasma Control: High quality work has been performed by the ITER team in this area. However, there are a number of outstanding issues, especially in plasma shape and position control, error field correction and AC losses that must be addressed more thoroughly.

In plasma shape and position control, a wide variety of plasma equilibria have been examined and the PF system provides considerable flexibility for ITER. Work remains especially in the evaluation of the newly proposed coil set, although initial results indicate that it provides improved control capability. The modified backplate design with the higher resistivity first wall increases the vertical instability growth rate and will negatively affect the plasma controllability. The dynamic

control analysis of this new configuration should be carefully evaluated before the new backplate design is adopted.

The magnetic field error correction coils proposed in the IDR and the DDR are presently being redesigned based on recent physics input concerning the importance of correcting multiple modes. While the new design provides increased flexibility, many questions remain in determining TF and PF coil placement accuracy, the effect of cool down, techniques to accurately measure error fields prior to and during machine operation, and the effect of Incoloy in the coils and ferromagnetic inserts in the TF coil. The use of modest amounts of lower voltage neutral beam injection for rotation should be evaluated given the uncertainties in the error field correction.

A variety of off-normal and transient events have been specified and study of the control system response to those events is on-going. However, control systems response to off-normal events presents potentially the most serious obstacle to ITER achieving its operational requirements of acceptable plasma control and pulse duration. The biggest uncertainty with the largest impact occurs when the control system tries to respond to large repetitive changes in the plasma, e.g. the ELM. The ELM characteristics used as input to the analysis are purely empirical with large error bars. When applied to plasma control, the large error bars translate into uncertainty in the power and time derivatives of power required to control the plasma. For AC loss calculations, the uncertainty in the ELM specification results in a large uncertainty in the maximum pulse duration that the cryogenic system can support.

B. Diagnostics: The diagnostics concepts are based on successful experience from existing tokamaks and, with careful implementation on ITER, they will fulfill the physics requirements. However, the EDA effort in diagnostics will not result in designs detailed enough to be ready for fabrication. The level of effort for the diagnostic design should be increased, with highest priority given to those diagnostics needed for machine safety and plasma control. The visibility of the diagnostics interfaces should also be increased so that they are seen as part of the overall design, and not as a separate entity.

There are inconsistencies between the diagnostic needs for plasma control in the physics assessment sections of the DDR, and the classification of required measurements in the diagnostics section. The control needs would indicate that more diagnostics should be in the class designated “for machine protection and plasma control.

The survivability of optical components is the highest risk technical concern for diagnostics, and this has been identified as a high priority R&D area. Most optical diagnostics will be dependent on mirrors very close to the plasma. The maintenance of adequate optical quality for these mirrors in the presence of neutral particle bombardment and radiation is questionable. This is particularly true in the divertor region.

C. Computer and Data Handling: ITER experimental operations present a complex, interactive environment that places considerable demands on computations systems supporting controls, data acquisition, integrated remote operation, and scientific analysis. The proposed hierarchical, distributed network coordinated by a supervisory system is motivated by requirements for real-time interaction, the volume of machine and scientific to be data acquired, and support for remote operations. This approach naturally extends to Wide Area Network (WAN) access but requires attention to access security and network connectivity performance. A reasonably well-posed philosophy defining the overall structure is developing. Much of the detailed design has been delayed until a later phase. Given the current, rapid development of networks and computer technology, this approach seems reasonable.

VI. Assessment of Confidence in Performance and the Degree of Operational Flexibility

ITER is clearly of the scope and scale required to explore extended-pulse, self-heated fusion plasma physics. However, in assessing ITER's anticipated performance, it is important to do so in the context of ITER as a scientific experiment — the first attempt at magnetic fusion ignition and controlled burn. In particular, to reach its peak performance, ITER will extend issues such as confinement, pulse-length and alpha-heating effects far beyond those attained in present day tokamaks. As such, predictions for its performance cannot be made precise, given the experimental nature and goals of the ITER program. The best that can be given are predictions of most probable performance, together with the associated uncertainty, for each of the individual aspects and hence for ITER as a whole. In the end, the judgment that must be made, as with any scientific experiment, relates to the balance between design risk and design conservatism, given the present state of knowledge and the objectives and goals of the experiment.

CONFIDENCE IN PERFORMANCE PROJECTIONS.

Finding and Conclusion: *In the Panel's estimation, based on extrapolated tokamak confinement data, the expected performance of ITER's base operating mode (ELMy H-mode confinement) ranges from that of fusion ignition ($Q \approx 1$) to a moderately self-heating burning plasma ($Q \sim 4$). (Here Q is the ratio of fusion power produced to energy input to sustain the plasma.) There is high confidence that ITER will be able to study long pulse burning plasma physics under reduced conditions ($Q \gtrsim 4$), as well as provide fundamental new knowledge on plasma confinement at near-fusion-reactor plasma conditions. Achieving long pulse ignition cannot be assured but remains a reasonable possibility.*

A. Confinement And Transport

Recent years have brought significant progress in understanding present tokamak plasma transport and confinement, and in the development of techniques to make performance projections for larger devices. The ITER design activities have stimulated and contributed to this progress. Despite this recent progress, and because ITER aims for regimes never before produced, the energy confinement and energy gain cannot be predicted precisely. Moreover, specification of the uncertainty in the projection cannot be evaluated rigorously. The projections for ITER performance arise from a combination of empirical scalings and approximate physics-based models with results which are partly subjective.

There are three techniques that are potentially useful for projecting ITER confinement and performance: global database scaling, non-dimensional scaling and one-dimensional (1-D) transport

modeling. However, the quantitative projection to ITER is currently based only on the global database scaling. Applicability of the sole plasma-physics-based non-dimensional scaling method is limited because of the closeness of the ITER operating point to the H-mode threshold and the Greenwald density limit (n_G); as a consequence, there is uncertainty as to whether the scaling in ρ^* (ratio of gyroradius to machine size) can be extended from present machines to ITER. The 1-D transport models are not used quantitatively because there is still no community-wide consensus on the validity and applicability of the models. In the U.S. fusion community, it is generally agreed that the leading candidate to account for much of the core transport is the class of microinstabilities driven primarily by ion temperature gradients (ITG modes), but agreement has not been reached on the quantitative predictions.

The Panel finds that the uncertainty in the projections to ITER confinement remains large. The most important reasons for this uncertainty are: the complexity of transport in tokamaks, especially in the improved H-mode confinement regime; the proximity of the ITER operating point to predicted, but imprecisely known, limits (H-mode threshold, density limits, “soft” macroscopic stability limits, etc.); and the deviation of the ITER operating point from that represented by most present tokamak experiments. In addition, the present tokamak experience, especially as represented by the bulk of the H-mode database, is characterized by densities well below the Greenwald limit, significant flow speeds, and powers well above the H-mode threshold. The ITER operating point is close to the H-mode power threshold, is close to the Greenwald density, has reduced flow speeds, is near the non-ideal stability limit, and uses a highly dense radiating divertor. Because there is experimental and theoretical evidence that these operational conditions lead to reduction in the plasma confinement, we consider the 6 seconds quoted in the DDR to be optimistic for the baseline high-density ELMing H-mode operational scenario. However, the extent of the reduction as extrapolated to ITER is highly uncertain, and might be ameliorated at least in part by improvements in fueling (e.g., high-speed and/or inside launch pellet injection, compact toroid injection, and/or low-voltage neutral beams if developed for ITER) or by ITER's tightly baffled divertor design.

The DDR quotes a confinement time of 6 seconds, with a 95% confidence level of $\pm 30\%$. Although a rigorous evaluation of the 95% confidence level is beyond the scope of this review, a value $\pm 50\%$ seems more appropriate. Starting from the DDR 6 sec confinement time, this corresponds to a range in confinement of approximately 3 to 9 seconds and a range in Q of approximately 4 to infinity (ignition). At the lower end of this range, ITER would not meet the controlled ignition and extended burn objectives as outlined in SWG-1. However, there is high confidence that ITER would be able to address many issues of long pulse burning plasma physics, albeit under driven conditions.

The Panel recognizes that these physics issues are complex and multifaceted, and not likely to be fully resolved prior to the FDR or the end of the EDA. We therefore recommend a research program directed at their longer-term resolution. Nevertheless, we should expect progress in each confinement projection technique (database scaling, non-dimensional scaling and one-dimensional modeling), with the goal of using all three in the FDR. The use of physics-based projections is especially important for gaining acceptance in the broader physics community. We believe that reducing the uncertainties in the present data and in the projections will require focused effort; the differences in the data from different devices as well as in the projections from the three different techniques need to be understood.

The Panel recommends emphasis on the present scientific effort to more fully integrate theory, modeling and experiment to provide physics-based models for projecting ITER performance. Specifically needed are experiments to test the stiffness of ITG-based models, theory and numerical simulations that clarify the origin of the stiffness in the ITG models, and experiments and theory to develop a better physics understanding of the edge pedestal height. We further recommend work on experiments, analysis, and theory to understand and predict better the H-mode power threshold and the proximity of the threshold to the ITER operating point. Also needed are experiments and theory to predict better the H-mode edge conditions. Additional experimental data, which is more representative of the ITER operating point, is needed for inclusion in the global and profile databases, and development of scaling relations including recently available data is needed.

The most solid and rapid progress in physics understanding is likely to occur in the context of the international tokamak program. Understanding differences observed on various tokamaks is likely to result from experience (experiments, data analysis, theoretical interpretation) coming from detailed comparative studies on the several tokamaks. Therefore, we recommend that the US. fusion energy sciences program take a strong initiative in encouraging and promoting collaborative experiments on existing tokamaks. Scientists should be encouraged to engage in this collaborative endeavor, within the present framework of cooperation.

B. Macroscopic Stability Boundaries And Disruptions

The Panel agrees broadly with the DDR conclusion that ideal MHD stability is unlikely to limit ITER performance. However, significant uncertainties remain with regard to non-ideal MHD mode stability limits and their effects, as well as the reliability and lifetime of components as a consequence of the frequency of disruptions.

There is rapid progress in understanding the non-ideal stability limits on the basis of neoclassically driven tearing modes, yet the projection to ITER's parameters still involves a number of unknowns. Progress in the theory of neoclassically driven tearing modes is required before more quantitative comparisons with theory can be completed, and careful comparisons of the observed limits between tokamaks at beta values and collisionality near those projected for ITER are recommended. Long-pulse operation at the desired β_N values above 2 appears difficult based on the scaling (shown in the DDR) from a number of tokamaks. If neoclassical tearing modes do limit the performance in ITER, it is plausible that these instabilities can be stabilized by local current drive, although such stabilization has not yet been validated by experiment: the Panel recommends that these stabilization experiments be completed. ITER's operational point is a safe distance from the calculated ideal boundaries, although more systematic analysis including a broader range of profiles should be considered.

The $n/m = 1/1$ instability, which nonlinearly produces the sawteeth in tokamaks, can adversely affect ITER performance through: 1) possible loss of alpha particles from the combination of the instability and the large mixing radius ($r_{\text{mix}}/a \sim 2/3$); 2) reduction of fusion gain during the central temperature excursion ($\sim 40\%$) ; and 3) possible coupling to other instabilities that might lead to degraded confinement or disruption. The successful operation of present day tokamaks with sawteeth at ITER relevant parameters indicates this is likely not a serious concern, but improved validated models would increase our confidence.

The DDR has produced a relatively clear picture of the most important physical processes with respect to plasma disruption, including vertical motion of the plasma, halo currents and runaway electrons. The halo currents cause very high local electromagnetic forces on the blanket/shield and thermal loads on the divertor plates. The runaway electrons generated by disruptions could produce intense local wall damage. The empirical projection of the magnitude of the halo current and its asymmetry in the DDR is adequate, but further development of a validated theory/model is needed to reduce the uncertainty in the ITER projections. The capability of the components to withstand the local and global loads are addressed in Section V and in the subpanel reports included as appendices. The DDR indicates a 30% disruption frequency in the early lifetime of the device decreasing to 10%. This disruption frequency is not sufficiently supported by well-documented data from any of the leading tokamak experiments operating near the ITER relevant stability bounds for long duration pulses. The Panel recommends that dedicated experiments on present tokamaks be carried out which systematically examine whether discharges operating at ITER-relevant values of v^* , beta and q (simultaneously) can successfully avoid disruptions for long pulses (>2 sec). Additionally, disruptivity near the Greenwald density needs to be evaluated.

C. Divertor And Fueling Systems

The Panel has reasonable confidence that the partially detached divertor design (PDD) will be able to handle the power and particles that result from a core plasma producing 1.5 GW of fusion power with plasma density in the range of $1 \sim 10^{20} \text{ m}^{-3}$. However, a number of uncertainties remain, and the simultaneous core performance and performance of the divertor needed to support the goals the Basic Performance Phase have yet to be proven: the operation of ITER will likely be needed to validate such simultaneous core and divertor performances.

Several requirements for the divertor operation may adversely impact the core performance. These are (1) increased edge and divertor radiation, (2) reduction of power flow across the last closed flux surface, by radiation, to near or below the H-mode threshold, and (3) contamination of the core plasmas by the injected impurities. In addition, the giant ELMs, if present, might cause reattachment and lead to unacceptable power loading. The choice of carbon fiber composites for the highest heat flux surfaces, combined with limited bakeout temperatures may make effective wall conditioning, disruption recovery, and limiting tritium codeposition more difficult. All of these issues are being intensively studied in the worldwide fusion program, but full resolution of these issues is unlikely before the end of the EDA. Significant work, both experimental and with theory/modeling, will be required in the years ahead to address all of these issues.

There is less confidence that the divertor/high-heat flux components, as presently designed, will perform adequately for the nuclear testing/steady-state Enhanced Performance Phase II of operation. The projected erosion and tritium deposition appear, even under possibly optimistic assumptions concerning disruption frequency, to be too large for the present design to survive under steady-state conditions. However, the divertor is explicitly designed to allow for redesign and component replacement, several times over the life of the machine, and whatever is learned between now and first operation of ITER, and even more importantly, during the operation of ITER itself, can be used to improve the design of the divertor and plasma facing components.

The fueling and pumping systems appear to be adequate from the point of view of providing and handling the particles. However, if deep core fueling is required, for example to achieve advanced operating modes, additional research and R&D will be required to develop a credible solution. At least three techniques have been proposed for core fueling. They are high speed pellets ($v > 4 \text{ km/s}$), inside launch conventional pellets ($v \sim 1 \text{ km/s}$), and compact toroid injection. Inside pellet launch ($v \sim 0.1 \text{ km/s}$) has shown some interesting preliminary results on ASDEX-U, but much more work needs

to be done to determine if this approach will be applicable on ITER. High speed pellets, with sufficient repetition rate, need to be demonstrated, and development of compact toroid injection is still in its infancy.

ADVANCED OPERATIONAL MODES, FLEXIBILITY AND HEATING.

Finding and Conclusion: *The Panel concludes that the DDR incorporates significant flexibility within the design and costs constraints, through multiple options to explore combinations of heating, fueling, shaping, and current drive control. As a consequence, the Panel has confidence that ITER will be able to take advantage of physics advances over the next decade to improve its performance over today's predicted base-operation. Additional analysis is called for to insure adequate flexibility to access advanced confinement regimes.*

The Panel notes that through advances in experimentation and understanding, most tokamaks have achieved improvements in their short pulse plasma performance (Q) by factors of 3 to 10 or more during their operational lifetimes. For example, recently many tokamaks, using the knowledge gained over the past several years, have developed methods to suppress turbulence and thereby routinely operate with confinement up to twice that predicted by the ITER H-mode scaling. More research is needed to develop a full understanding of these methods, how they extrapolate to larger steady-state tokamaks, and the reactor designs required to exploit them. These advanced tokamak modes of operation could provide increased probability of ignition and will likely play a major role in the Enhanced Performance Phase. The reverse shear scenario is now the leading candidate scenario for ITER steady state operation.

Such improvements require a hardware and operational flexibility which ITER's size and nuclear capability make awkward. The DDR has not chosen amongst the possible options for heating, fueling, and current drive control, but maintains multiple options in the design. A combination of these multiple options, when combined with the other aspects of flexibility like cross-section shape, are needed provide the experimentalists opportunities to develop improved operations scenarios for ITER. These advanced modes of operation will not be explored in the initial stages of operation, but later, after some experimental experience has been gained. At present, since four heating and current-drive systems are being allowed for and other options remain, it appears that sufficient flexibility for advanced tokamak operation can be provided, but additional analysis is need to assure that these systems can meet the requirements for flexibility. The Panel notes that the recently added poloidal field coils provide modest improvements in shape flexibility, but that significant improvements in shape flexibility could be obtained by developing an acceptable design for a non-monolithic central solenoid.

The advanced tokamak (AT) modes are the preferred scenario for steady-state operation. These modes operate at higher normalized beta, higher poloidal beta, and higher edge safety factor than the ITER reference scenario, and have higher performance because of enhanced stability and energy confinement. Significant development of the physics base for advanced confinement operation regimes can be accomplished at modest pulse lengths in the present research program. However, long pulse effects and the alpha-particle heating in a burning plasma will likely alter the plasma pressure and other profiles, and these effects can only be explored in an ITER-class device.

Unique MHD stability and disruption issues are associated with steady-state, lower current advanced operating modes. These challenges include: controlling plasma instabilities at high normalized beta; controlling both plasma current and plasma pressure profiles at high poloidal beta; and preparing plasma equilibria at low plasma current in the presence of significant toroidal field ripple. These challenges are currently being addressed by the ITER design team and an option for ripple reduction using magnetic "shims" is being investigated. However, additional research and analysis is needed to specify the required rotation for stability and how to maintain that rotation.

The present ITER poloidal field system is capable of accessing and exploring advanced tokamak operating modes. Extensive and significant calculations and simulations demonstrate that the proposed hardware systems can start up and maintain a variety of plasma equilibria, including "advanced" ones. However, the plasma shaping flexibility could be improved with an acceptable non-monolithic solenoid design. The capability of the possible heating and current drive schemes to access and sustain advanced modes needs to be more adequately assessed.

No single heating and current drive method can satisfy all of ITER's physics needs — start-up assist, heating to ignition, burn control, MHD instability control, current drive on- and off-axis, and rotation drive. In addition to inductive drive, four current-drive techniques are considered in the DDR: fast-wave, electron cyclotron, and lower-hybrid wave systems; and neutral beams. The four heating and current drive candidates have been developed to a substantial level and further R&D is continuing. The ITER JCT position that a selection of one or more preferred methods is neither necessary nor desirable at this time is appropriate.

The ITER divertor system should be able to handle AT equilibria. However, there may be limitations on the achievable pulse length or operational space. Because the divertor has a large volume and a modular and flexible design, future upgrades or modifications can be made to optimize its design specifically for AT modes, if required.

THE BASIC PERFORMANCE PHASE AND THE ENHANCED PERFORMANCE PHASE.

Finding and Conclusion. *The Design Team has focused its attention and resources so far on successful operation in the Basic Performance Phase with the view that the knowledge and experience gained in this phase will guide the Enhanced Performance Phase. Consequently, achieving the Basic Performance Phase objectives looms large in the DDR design, and the Enhanced Performance Phase objectives have not been addressed beyond assuring capability of the facility to address those objectives. The Panel concurs with this approach.*

As specified in the requirements, ITER will have two operational phases, the Basic Performance Phase (BPP) and the Enhanced Performance Phase (EPP), each lasting about ten years. A detailed operational plan for the EPP has not been developed by the JCT, because such a plan will depend strongly on the plasma performance, operational experience, and knowledge gained during the BPP. However, it is foreseen that there will be somewhat less emphasis on the physics studies, and more emphasis on reliable operation to produce high neutron fluences, approximately 1 MW-a/m² over 10 years.

The DDR defines two candidate operational scenarios for meeting this fluence goal; (1) an extended burn with primarily ohmically driven current, but with current drive assist, and (2) a high bootstrap fraction steady state, reversed negative central shear scenario. The latter scenario will require significant advances in the physics understanding. It is expected that both operational scenarios, as well as others, will greatly benefit from on going research and experience in the BPP.

Achieving the neutron fluence level expected for the EPP will put increased emphasis on the capability of the divertor to handle the heat fluxes (possibly higher for the driven burn); and increased emphasis on the availability ($\gtrsim 10\%$), which will require low disruption frequency for the very long pulse discharges. The Panel notes that at the lower range of expected performance of ITER ($Q \gtrsim 4$), increased auxiliary power and/or increased availability might be required. The capability for additional heating and current drive must be incorporated into the baseline design. Although these goals are challenging, the Panel thinks the design is adequate to pursue them, and because the EPP will require a successful, BPP program, the Panel concurs that the approach taken in the design to focus on that phase is appropriate.

VII. Assessment of Environment and Safety

ITER is a large and complex device which will use tritium as a fuel and produce energetic neutrons as an output. As a result of neutron bombardment, the machine structure and surrounding materials will become activated. The ITER device will require a nuclear license to operate wherever it is sited. Yet, it is unlike any other device that has been licensed previously.

Finding and Conclusion: *The ITER team has an appropriate organization in place to address nuclear issues and has, in general, addressed these issues in an appropriate manner. The nuclear design effort has been the subject of a recent review by the four parties within the ITER framework and the work done has been documented in the Non-site Specific Safety Report (NSSR-1). The safety aspects of the design and analysis are adequate for this stage of the project.*

Detailed safety requirements have been established based on recognized international safety criteria. These limits aren't always as restrictive as U.S. limits. Safety requirements have been an integral part of the overall design requirements. Careful analysis has been done to show that the facility will operate within these requirements in both normal and accident scenarios. These analyses have been carried out using the best available understanding and computer codes. The project has as a design requirement the avoidance of the need to evacuate the general public following the most serious accident. A general project objective is that the dose to workers and the public be maintained as low as reasonably achievable (ALARA).

Public and Worker Safety.

The avoidance of the need for an evacuation of the public is important in meeting the licensing requirements of any potential sites and in determining public perception of fusion. ITER has adopted IAEA criteria in determining critical exposure levels for both workers and the public. In some cases, these are less restrictive than the U.S. standards. The ITER design sets a criterion of 50 mSv as the criterion for evacuation. They are able to demonstrate that they can remain under this limit for any credible accident. The U.S. criterion for no evacuation is 10 mSv. Thus to meet the requirements for licensing in the U.S. with no evacuation, ITER would need to demonstrate that they could meet the requirement of limiting the dose to 10 mSv.

The projected releases of airborne and waterborne tritium are high. According to the DDR, the projected waste water tritium concentrations of 1000 mCi/m³ exceed both the 2 mCi/m³ ITER

requirement for tritium contaminated water and the U.S. EPA drinking water standard. Thus ITER should design to more conservative limits to meet both their own internal limits and U.S. standards.

ITER has worked to anticipate and limit radiation to workers by providing several levels of confinement and defining remote maintenance procedures for areas and tasks which will be subject to high levels of radiation after even limited operations. The remote handling procedures for in-vessel components are extensive and considerable supporting R&D has been done. Attention has also been paid to radiation levels in a number of service areas around the machine, but the standards used are about five times higher than the U. S. standard. One important issue that needs to be addressed in more detail is the recovery from the failure of a remote maintenance system while positioned in an area of high radiation.

Nuclear Design. The ITER organization has done an effective job of assessing the radiation issues of the facility given the state of the design. They have identified a number of assumptions that have been made to complete the safety analysis in a timely manner. It is important that a well-defined mechanism be put into place to insure that the impact of deviations in the design from these assumptions and from changes in the design are properly reflected in the safety analysis.

The accountability of tritium, a radioactive material with substantial nuclear security concerns, is crucial to the operation of ITER. The need to have careful and accurate procedures in place has been driven home by the operation of TFTR (and JET in Europe). This has been done in the NSSR-1, but this account lacks adequate detail. One particular area of concern is the accounting of the tritium in the vacuum vessel where substantial amounts can accumulate on the walls, especially co-deposited in carbon first wall materials. There is no apparent method of accounting for the amount of material accumulated within the vessel. Furthermore, it will be essential to remove this material periodically (weekly to quarterly depending on the accumulation rate) and no effective means for doing this has been identified. The ability to bake at higher temperatures (300 C) than presently envisioned in the design would be a substantial asset here.

The operational criteria that need to be met to operate ITER within the defined safety envelope can substantially impact the availability of the facility. This will likely include safety tests, allowed inventories of tritium, staffing, isolation of critical areas for operations that might otherwise be open for maintenance, and the like. It is important that ITER identify their operational criteria and then assess the impact on availability.

ITER will produce significant amounts of highly radioactive fairly long lived nuclear waste both from ongoing activities such as the replacement of in-vessel components and from decommissioning. They result from the bombardment of the materials by fusion neutrons. These wastes are considerably less hazardous than those from a nuclear fission reactor, but nevertheless represent significant hazards. These wastes can be minimized by the careful selection of materials. ITER has done this to some extent, particularly in the blanket design, but their ability to do so is limited by the lack of a technology base for the best materials. The needed data base is substantial and would be appropriate for commercial reactors. ITER has made reasonable material choices given its role as an one-of-a-kind experimental device. It is important that the JCT continue to work to minimize the high level waste products as the design is completed.

Non-Nuclear Safety.

There are a number of non-nuclear safety issues arising from the operation of ITER. They have generally been recognized and largely must be dealt with within the regulations of the host country. Large amounts of electrical energy will be required to power the coil systems, but the techniques are conventional and it is reasonable to expect that the work can be done within the practices of the host country. A single point electrical grounding system has been identified. Static magnetic fields will be present during operation and zones of exclusion have been designated which will keep worker exposure within accepted limits.

The fire suppression system remains to be laid out in detail. Experience has shown that these systems have the potential of seriously interfering with the installation and operation of other experimental systems. Care should also be taken to lay out evacuation paths from the main experimental hall given its size, below ground location, and the hazards present.

VIII. Cost and Schedule

This Cost and Schedule review focused on the ITER Post-EDA and construction cost and schedule estimates in the DDR and supporting documents. The JCT estimate includes the elements required for the basic performance of ITER. The IDR includes the estimates for construction, R&D and prototypes during construction, design after the end of the EDA, construction management, construction inspection and oversight, acceptance testing, pre-operational checkout, and commissioning. It also includes estimates for the shared cost of operation and decommissioning, but operations and decommissioning were not covered in any detail, and are not commented on.

The cost and schedule development process used by the JCT was based on a detailed set of procedures and formats that facilitated a standardized and consistent cost and schedule estimate. For many components, and for virtually all of the tokamak components, industrial estimates have been obtained from multiple Parties (herein to be understood as industries of those Parties) in preparation for the Interim Design Report (IDR). For some components, estimates were obtained from a single Party, and for buildings, diagnostics, and machine tooling they were internally generated by the JCT. The IDR Cost Estimate represented a bottoms-up estimate of almost every element of ITER.

Findings and Conclusion. *In the Panel's judgment, the JCT has done a disciplined and thorough job in gathering the complex data from diverse parties and developing a self-consistent cost and schedule data-base predicated on sound cost and schedule estimating methodologies. Estimates for components and systems are primarily based on industrial estimates from multiple parties, and have been extensively analyzed and processed to insure credibility, completeness and accuracy. Overall, the Panel judges the cost estimate to be reasonable and sound for this stage of the project. The Panel does note that the plan is a success-oriented one, in that there is little or no budget or time allotted to accommodate unforeseen problems that may arise. An efficient management structure and procurement system, taking maximum advantage of industrial competition in bidding, is required during construction to meet the aggressive cost and schedule goals of the project.*

To accommodate the different currencies, practices, and industrial indices of the ITER parties, the JCT developed a reasonable normalization procedure to arrive at the cost of each project element in 1989 dollars. The JCT then generally chose the lowest of the credible estimates as the cost of each item. In practice, an aggressive procurement process which takes full advantage of industrial competition must be employed to realize these costs, and make this a valid estimating process. The DDR estimates exclude certain costs, including costs to be borne by the host (site, infrastructure, etc.)

and the resources already spent on the CDA and EDA phases. To accommodate the practices of the various parties to the ITER, a contingency budget has not been included in the overall estimate. Contingency is based on project requirements relative to the current state of the art, and on project uncertainties that could affect specific cost elements including potential technical, cost, and schedule changes. Provision for adequate funding, including contingency, will need to be accommodated in cost estimates for the elements the US will provide as its responsibility in participation during construction.

Recognizing the exclusions enumerated above, the JCT cost and schedule estimates are quite complete. The JCT has indicated that a new bottoms-up comprehensive industry estimate of the ITER cost is beginning in support of preparation for the Final Design Report.

The following assumptions have been made in creating the ITER DDR Cost Estimate:

- That the four parties will share approximately equally in the costs for ITER. If not, then lowest credible estimates cannot be used, because of unequal industrial participation by the parties, and a commensurate loss of competition.
- That parties will provide the requested funding profile on schedule and that the parties are committed to maintaining the proposed ITER construction schedule.
- That the post EDA R&D will be completed and successful prior to contracting for component manufacture. The R&D program is currently lagging due to shortfalls in funding.

ISSUES AND RISKS

The two most important elements leading to cost indeterminants are: (1) the management organization that is established by the parties for implementation of construction, and (2) the actual schedule achieved for construction. Both of these elements impact the efficiency of implementation which has a profound impact on costs.

Further risks that the Panel has identified are:

- The present cost estimate is based on the assumption that the design, fabrication, and assembly and installation of certain components important to safety, namely the vacuum vessel and the vacuum vessel pressure suppression system, the cryostat, and the primary heat transport system which is to Section VIII of the ASME Code or equivalent, will be accepted by the Regulatory Authorities

- Nb₃Sn conductor for the TF, CS, and two of the PF coils. The total quantity of strand needed for these magnets is 1200 tonnes. For this quantity to be delivered in the time required by the schedule, the capacity of the world producers of the Nb₃Sn strand will have to more than triple. Strand producers have indicated that the increased production is achievable, but there is a question as to whether the other Parties can increase their production further if the US is limited in production by their limited contribution to ITER. It is also possible that the Large Hadron Collider Project, and various superconducting RF accelerator projects will place an additional significant demand on the Nb production capacity.
- Incolloy jacket material. The US is presently the sole provider of Incolloy. There will likely be a need for a second supplier; and it is anticipated that this will be accomplished by a licensing arrangement.
- Due to initial conservative costing, there is an opportunity to experience some reduction in the costs of the buildings as the design progresses. The JCT has indicated that the FDR estimate will reflect the more mature design.

ITER performance shortfalls that would require changes to the tokamak or its subsystems. Examples identified by the Physics sub-panel are:

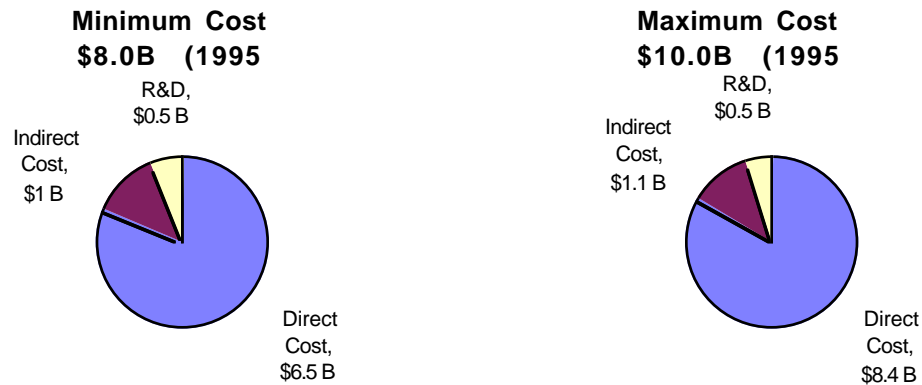
- Deeper fueling penetration to allow operation above the Greenwald density limit, achieved either by modifications to injection.
- Increased plasma heating power.
- An additional 50MW of lower energy neutral beams (80keV) has been suggested by the US in this review, to better control the plasma rotation.
- Reversed Central Shear (RCS) plasmas may require off-axis RF current drive. Analysis shows that 100 MW of ECH will be required to support RCS plasmas.

Many of the costs for increased power (heating) might be appropriately accommodated within the provisions for “capital improvement” in the proposed operating budgets for the basic performance phase, and would not impact construction costs. There are operation related issues that if not resolved could impact cost or schedule.

- The design of diagnostics required for machine protection and plasma control appear to be lagging.
- The need to provide more flexibility to accommodate alternate divertors.

In order to achieve the proposed magnet production schedule in the light of the delays already encountered from funding shortfalls, it will be necessary to have TF manufacturing and cold testing done at two facilities.

The cost for the ITER construction phase are estimated to range between \$8 B and \$10 B in 1995 \$. The distribution of the costs are shown below.



Direct construction costs include all components, systems structures, buildings, materials, and construction labor to construct the complete ITER facility that would operate during the basic performance phase. Indirect costs include project management, procurement, engineering, support of construction, and pre-operational testing / startup. R&D includes the cost of R&D scheduled, but not performed during the EDA (~116M 1995\$) and R&D forecast as being needed during construction.

Generally, this is a success oriented plan, in that there is little or no budget or time allotted to accommodate problems. Additionally, the discipline which has been imparted to the project by the now departing administrative officer must be continued to guarantee further progress. Finally, an efficient management structure and a procurement system which takes maximum advantage of industrial competition is required to meet the aggressive cost and schedule goals of the project.

